

Search for relativistic beaming in ultraluminous X-ray sources

L. Foschini^{†1}, G. Malaguti[‡], G. Di Cocco[‡], M. Cappi[‡], M. Dadina[‡], L.C. Ho[‡]

[†] Istituto di Astrofisica Spaziale e Fisica Cosmica del CNR, Sezione di Bologna (formerly iTeSRE–CNR). Via Gobetti 101 – 40129 Bologna (Italy).

[‡] The Observatories of the Carnegie Institution of Washington
813 Santa Barbara Street, Pasadena, CA 91101, USA

Abstract. The nature of the ultraluminous X-ray sources (ULX) is still to be understood. Several hypotheses have been suggested to explain the high X-ray luminosity: stellar mass black holes with emission collimated by relativistic effects or anisotropies in the accretion disk, intermediate mass black holes, young supernovae remnants, background active galactic nuclei. To discriminate among the above hypotheses, the search for relativistic effects can be a valuable “pathfinder”. Here we propose a list of ULX candidates suitable to show relativistic beaming.

1. Introduction

One of the most intriguing and exotic prediction of the theory of General Relativity is the existence of a spacetime singularity with around it a region bounded by an event horizon (i.e. a *black hole*). Although the black hole was predicted early in 1916 by K. Schwarzschild (with some interesting pioneers such as Laplace), the proofs – still indirect – of its existence came only at the end of the XX Century, when the first satellites for X-ray astronomy were launched.

Now, the black holes (BH) are divided into three categories, according to their mass: stellar (e.g. Cyg X–1), intermediate, and supermassive (AGN). The existence of intermediate mass black holes was suggested after the discovery of the ultraluminous X-ray sources (ULX) and it is still controversial. The ULX are non–nuclear point–like sources with luminosity – calculated as they are in the host galaxy – exceeding the Eddington limit for a neutron star (see Foschini *et al* 2002a for a discussion on the luminosity threshold). They were known since the *Einstein* satellite (Fabbiano 1989), but it was with *Chandra* that it was realized that ULX are common in nearby galaxies (Fabbiano *et al* 2001).

Now, ULX are a well known reality, but their nature is far from being known. Several hypotheses have been suggested: the most interesting would be that ULX are intermediate mass black holes ($10^2 - 10^5 M_\odot$, see e.g. Colbert and Mushotzky 1999, Miller *et al* 2002). This could have a great impact also in the evolution of the host galaxies and provide a clue between the stellar mass BH and the supermassive BH in the AGN. Other hypotheses to explain ULX are: Kerr BH (Makishima *et al* 2000), anisotropic emission from an accreting BH (King *et al* 2001), slim accretion disk (Watarai *et al* 2001), inhomogeneities in a radiation–pressure dominated accretion disk (Begelman 2002), emission from a relativistic beamed jet (Körding *et al* 2002, Georganopoulos *et al* 2002), an extragalactic version of the microquasar model by Mirabel and Rodríguez (1999). There could be also the possibility that we are facing with young supernovae remnants expanding in an interstellar matter rich of nitrogen (Schlegel 1994) or, simply, with AGN of background (Foschini *et al* 2002c).

Here we propose a list of ULX candidates suitable to display relativistic beaming, being examples of microquasar in nearby galaxies. We would like to stress that the present list is only a starting point for further researches, and therefore is far from being complete.

¹ E-mail: foschini@bo.iasf.cnr.it.

2. What to search for and with what instrument

From the observations of stellar mass black holes in the Milky Way, it is known that they can exist in different states. The two main are named “soft (high)”, where the thermal contribution from the accretion disk dominates the X-ray emission, and “hard (low)”, where the main contribution comes from a non-thermal power law (cf, for example, Nowak 1995). The hard state is generally coupled with a relativistically beamed jet with optically thick emission of synchrotron radiation in the radio-optical domain (Fender 2001), but it has been recently proposed that this radiation can extend up to the X-ray domain. In this case, the emitted radiation can be generated either in the extended jet structure (Atoyan and Aharonian 1999) or in the region close to the accretion disk (Markoff *et al* 2001). Other mechanism able to produce X-ray photons are the inverse Compton scattering of the relativistic electrons from external seed photons (from the companion star, e.g. Georganopoulos *et al* 2002) or from the photons of the accretion disk (cf Nowak *et al* 2002). In the observation of ULX we move to nearby galaxies, so that it is much more difficult to find the proofs of a relativistically beamed emission with the actual technology. Nonetheless, it is possible to set up a first tentative scenario.

2.1. Radio emission

The easiest way could be to search for the radio emission, but when scaled to the distances of the nearby galaxies, we realize that it is a task not so easy (and indeed, the radio emission from ULX is still poorly known).

One of the most known Galactic microquasar candidates, GRS1915+105, is characterized by episodes of radio flares up to 1 Jy during its active state, which are superimposed to a “plateau” of about 100 mJy at $\nu \approx 1 - 10$ GHz (see Atoyan and Aharonian 1999). Scaling the distance to a typical nearby galaxy 5 Mpc far, the peak flux drops down to 6 μ Jy (and this would be the best case).

There are actually a very few cases of radio emission from ULX: the first case was later identified as a BL Lac of background (Foschini *et al* 2002c). Another case has been recently found by Kareet *et al* (2003): the ultraluminous source 2E 1400.2 – 4018 in NGC5408 showed a flux of 0.26 mJy at 4.8 GHz and the authors suggested that this could be – together with the X-ray spectrum (from Chandra data) – the signature of a microquasar. If confirmed (no redshift was available at the date of the publication), this would represent a very powerful ULX, about two order of magnitude higher than the peak of GRS 1915 + 105 when scaled to the same distance. The most promising radio detection appears to be that of ULX M81–X6: 95 μ Jy at $\lambda = 3.6$ cm (Swartz *et al* 2003). So, the hunt for the radio emission is still well open.

2.2. X-ray emission

Most of ULX show thermal emission well fitted with the multicolor blackbody accretion disk (MCD, cf Makishima *et al* 2000). As known, the thermal contribution in the hard state is generally below the 20% of the total emission in the X-ray domain; in addition, the MCD model can also be explained well by the emission from the innermost stable circular orbit of the accretion disk of an intermediate mass BH (Miller *et al* 2002) or from a spinning BH (e.g. La Parola *et al* 2001), depending on if the disk is cold ($kT \approx 0.15$ keV) or hot ($kT \approx 1 - 2$ keV), respectively.

Therefore, to search for the evidence of jets, the best option appears to be to look at those sources displaying spectra fitted with power law models. In addition, the presence of relativistic beaming could be inferred by the absence of reflection features.

Moreover, it is worth noting that the hard state displays an evident time variability (up to 50% rms below 1 Hz, cf Fender 2001). However, this topic has been investigated poorly, because of the necessity to have very long exposure, possibly spaced by months or years (e.g. Fabbiano *et al* 2003).

2.3. Caveats: how different detectors see the spectrum of the sources

The spectral data available on ULX are mainly from three satellites: ASCA, Chandra, and XMM–Newton. ASCA had high throughput of photons, but the low spatial resolution make it possible to have often contamination from other nearby sources. Chandra, while having an exceptional angular resolution ($< 1''$), has an effective area that drops above the peak energy of the multicolor disk blackbody model

Table 1. List of ULX candidates with possible relativistic beaming as inferred from spectral characteristics (i.e., best fit with a power law model). Columns: (1) Name of the source; (2) right ascension and declination (J2000); (3) absorbing column density [10^{21} cm^{-2}]; (4) photon index; (5) X-ray luminosity in the 0.5 – 10 keV energy band [$10^{38} \text{ erg s}^{-1}$]; (6) reference paper; (7) X-ray satellite that made the observation. For $N_H = \text{Gal.}$, it means that no additional absorption is found to be significant. The luminosities were calculated using distances from Ho *et al* (1997), who considered an infall velocity of 300 km/s for the Local Group, $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and the distance of the Virgo Cluster of 16.8 Mpc.

Name (1)	Coordinates (2)	N_H (3)	Γ (4)	L (5)	Reference (6)	Satellite (7)
Antennae-37	12 : 01 : 55.0, -18 : 53 : 15	2.6 ± 0.5	1.7 ± 0.2	102	Zezas <i>et al</i> 2002	Chandra
Antennae-44	12 : 01 : 56.4, -18 : 51 : 58	1.0 ± 0.3	1.9 ± 0.1	129	Zezas <i>et al</i> 2002	Chandra
NGC720-40	01 : 53 : 01.7, -13 : 46 : 31	< 4	1.3 ± 0.7	110	Jeltema <i>et al</i> (2002)	Chandra
NGC3486-ULX1	11 : 00 : 22.4, +28 : 58 : 18	Gal.	2.2 ± 0.5	5.0	Foschini <i>et al</i> (2002b)	XMM
NGC3941-ULX1	11 : 52 : 58.3, +36 : 59 : 00	Gal.	1.9 ± 0.2	74	Foschini <i>et al</i> (2002b)	XMM
NGC4501-ULX2	12 : 32 : 00.8, +14 : 24 : 42	Gal.	2.3 ± 0.4	37	Foschini <i>et al</i> (2002b)	XMM
NGC4565-ULX2	12 : 36 : 14.8, +26 : 00 : 53	6 ± 5	1.7 ± 0.6	16	Foschini <i>et al</i> (2002b)	XMM
NGC4565-ULX4	12 : 36 : 17.4, +25 : 58 : 54	Gal.	1.9 ± 0.1	25	Foschini <i>et al</i> (2002b)	XMM
NGC4565-ULX6	12 : 36 : 27.8, +25 : 57 : 34	Gal.	1.5 ± 0.3	9.0	Foschini <i>et al</i> (2002b)	XMM
J123030.8+413911 (NGC4485/4490)	12 : 30 : 30.8, +41 : 39 : 11	8 ± 3	1.8 ± 0.3	46	Roberts <i>et al</i> 2002	Chandra
NGC4490-X1	12 : 30 : 36.3, +41 : 38 : 37	4 ± 2	1.8 ± 0.3	26	Roberts <i>et al</i> 2002	Chandra
NGC4490-X2	12 : 30 : 32.8, +41 : 39 : 18	5 ± 2	1.7 ± 0.3	26	Roberts <i>et al</i> 2002	Chandra

generally used for ULX ($kT \approx 1 - 2 \text{ keV}$); in addition, with comparison to ASCA effective area, there is another sharper drop in the effective area just above 4 keV. On the other hand, XMM-Newton appears to be a good compromise between spatial and spectral behaviour to observe and study the jetted ULX in nearby galaxies: while the angular resolution of the EPIC-MOS cameras is around $1.1''$, the effective areas – particularly of the PN camera – can guarantee a high throughput also at energies above 2 keV, so providing good measurement in the region of hard-X rays, where it is expected to be dominated by the tail of the power law.

3. A list of candidates

As stated in the Sect. 2.3, ASCA has a very low spatial resolution, although the high throughput allows to get good spectra (e.g. Makishima *et al* 2000, Mizuno *et al* 2001). Sometimes ULX are confused with a low luminosity AGN or, alternatively, that the observed “low luminosity AGN” is, in reality, an ULX. Two cases of this type occurred in NGC4565 and NGC3486 respectively (cf Foschini *et al* 2002b). So, to avoid further contaminations, we adopted the – perhaps too much – drastic decision of not using the ASCA data. We use, as starting point, the Chandra and XMM-Newton data, but it is worth noting that ASCA observations could be a good “pathfinder” for further researches.

In the Table 1, a list of ULX candidates with possible relativistic beaming as inferred from the power law model. In the hard state, the photon index is $1.3 - 1.9$ (cf Ebisawa *et al* 1996, Fender 2001) and we considered as possible candidates those sources with Γ in the above interval, also by taking into account the statistical errors. It is worth noting that Zezas *et al* (2002) have found in the Antennae galaxies several other ULX best fitted with a power law model, but the Γ values were incredibly high (up to 7!). We do not consider these sources, but given the characteristics of the effective area of Chandra, it is possible to guess that the same sources when observed with XMM-Newton could display flatter indexes. Therefore, these sources (namely, n. 5, 13, 29, 33) need for additional investigation.

In addition to the ULX of Table 1, we also propose another set of candidates to display relativistic beaming, but now as inferred from time behaviour. In this case, the best fit model is no more the power law, but we also consider the blackbody models. The presence of the relativistic beaming is now inferred from the high time variability (up to 50% rms). This second set is shown in Table 2.

Table 2. List of ULX candidates with possible relativistic beaming as inferred from time variability studies. Columns: (1) Name of the source; (2) right ascension and declination (J2000); (3) absorbing column density [10^{21} cm^{-2}]; (4) photon index, if the best fit is a power law, or kT [keV] in the case of blackbody; (5) X-ray luminosity in the 0.3 – 8 keV energy band [$10^{38} \text{ erg s}^{-1}$]; (6) reference paper; (7) X-ray satellite that made the observation. For $N_H = \text{Gal.}$, it means that no additional absorption is found to be significant. The luminosities were calculated using distances from Ho *et al* (1997), who considered an inflow velocity of 300 km/s for the Local Group, $H_0 = 75 \text{ km}\cdot\text{s}^{-1}\text{Mpc}^{-1}$, and the distance of the Virgo Cluster of 16.8 Mpc.

Name (1)	Coordinates (2)	N_H (3)	Γ or kT (4)	L (5)	Reference (6)	Satellite (7)
2E1400.2 – 4108 (NGC5408)	14 : 03 : 19.6, –41 : 22 : 59	4 ± 2	$\Gamma = 2.8 \pm 0.3$	110	Kareet <i>et al</i> (2003)	Chandra
M51–X7	13 : 30 : 01.0, +47 : 13 : 44	Gal.	$\Gamma = 1.3 \pm 0.2$	19.8	Liu <i>et al</i> (2002)	Chandra
M81–X6	09 : 55 : 33.0, +69 : 00 : 33	2.2 ± 0.1	$kT = 1.0 \pm 0.1$	27	Swartz <i>et al</i> (2003)	Chandra
M101–P104	14 : 03 : 36.1, +54 : 19 : 25	Gal.	$\Gamma = 2.6$	2.0	Mukai <i>et al</i> (2003)	Chandra

4. Final remarks

Even though during the latest years, the efforts to understand the nature of ULX dramatically increased, these enigmatic sources are still poorly known. Among the different available theories, it is worth mentioning the microquasar model. To search for proofs in favour of this model, it is necessary to study the spectral and timing behaviour of the ULX with dedicated observations. The list of ULX presented in this work is a first step toward this direction.

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References

- Atoyan A M and Aharonian F A 1999 *MNRAS* **302** 253
 Begelman M 2002 *ApJ* **568** L97
 Colbert E J M and Mushotzky R F 1999 *ApJ* **519** 89
 Ebisawa K *et al* 1996 *PASJ* **48** 59
 Fabbiano G 1989 *Annu. Rev. Astron. Astrophys.* **27** 87
 Fabbiano G *et al* 2001 *ApJ* **554** 1035
 Fabbiano G *et al* 2003 *ApJ* **584** L5
 Fender R 2001 *MNRAS* **322** 31
 Foschini L *et al* 2002a *Inflows, outflows, and reprocessing around black holes* edited by I Cagnoni (Como: University of Como) p. 88
 Foschini L *et al* 2002b *A&A* **392** 817
 Foschini L *et al* 2002c *A&A* **396** 787
 Ho L C *et al* 1997 *ApJS* **112** 315
 Jeltama T E *et al* 2002 *ApJ* accepted (*astro-ph/0211192*)
 Kareet P *et al* 2003 *Science* **299** 365
 King A R *et al* 2001 *ApJ* **552** L109
 Körding E *et al* 2002 *A&A* **382** L13

- Georganopoulos M *et al* 2002 *A&A* **388** L25
- La Parola V *et al* 2001 *ApJ* **556** 47
- Liu J F *et al* 2002 *ApJ* **581** L93
- Makishima K *et al* 2000 *ApJ* **535** 632
- Markoff S *et al* 2001 *A&A* **372** L25
- Miller J M *et al* 2002 *ApJ* **585** L37
- Mirabel I F and Rodríguez L F 1999 *Annu. Rev. Astron. Astrphys.* **37** 409
- Mizuno T *et al* 2001 *ApJ* **554** 1282
- Mukai K *et al* 2003 *ApJ* **582** 184
- Nowak M A 1995 *PASP* **107** 1207
- Nowak M A *et al* 2002 *MNRAS* **332** 856
- Schlegel E 1994 *Ap. J.* **424** L99
- Swartz D A *et al* 2003 *ApJS* **144** 213
- Watarai K *et al* 2001 *ApJ* **549** L77
- Zezas A *et al* 2002 *ApJ* **142** 239